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ATMOSPHERIC WIND AND DIFFUSION FROM ANALYSIS OF AN SF_6 RELEASE AT 350 km ALTITUDE

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31 July 1984

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PREPARED FOR

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Analysis of intensified video imagery of the nighttime release of SF_6 at 350 km altitude has provided the first measurements of atmospheric diffusion and wind velocity at high altitude. The measurements apply to validating models of atmospheric dynamics and of the reactions and transport of the released species. Images taken through a wide angle lens

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FOREWORD

The work reported here involved analysis of image intensified video records of a release of sulfur hexafluoride into the upper atmosphere. Images were digitized using the AFGL Coordinate Digitizer/Image Analyzer System and most of the data analysis to determine glow position, motion, and growth (diffusion) was performed using the system's minicomputer controller.

The author wishes to express thanks to C.A. Forsberg, AFGL/LID (Contract Monitor) for his continued encouragement and support, to E. Weber and R. Gowell of AFGL/LIS for helpful discussions and for supplying information about the imaging system which recorded the glow (flown on the AFGL Ionospheric Observatory aircraft (KC135/53131)), and to C.C. Rice for assistance in compiling this report.

List of Illustrations (continued)

List of Tables

payload was launched from Wallops Is., Virginia and the release occurred at 348 km altitude at 5:20 UT on 9 Nov 1983.

Subsequent sections of the report discuss methods used for determination of video camera pointing from the recorded star fields, reduction of range to the glow, analysis to determine growth of the cloud, and cloud motion (atmospheric wind) derivation from its time dependent positions.

2. Determination of Camera Orientation

Triangulation camera orientation is normally determined very accurately using vector mathematics to relate image plane locations of star images with their known equatorial coordinate system positions (right ascension α, and declination δ). Data for several stars and their images are processed utilizing the methods of Ref's 2-3 to establish the focal length of the camera and the direction of the optic axis in space. The direction vector is intially calculated in the equatorial system but is easily expressed in other coordinate systems by means of coordinate transformations (rotations about coordinate axes). Typical precisions (standard deviations) of the measurements for a short focal length lens (f = 25 mm) are 0.05 cm for focal length, and 0.01° for azimuth, elevation, and horizonal tilt (orientation expressed in the horizon coordinate system where the horizonal tilt is the angle between the camera x-axis and the horizon). Note that procedures which are normally applied when lens distortion is negligible (i.e. a single focal length completely describes the image field) were expanded and adapted for the 90° lens used. Furthermore, the small number of stars visible reduced the precision of the camera orientation.

Digitization of the video and determination of image plane coordinates of star and glow images was performed on the AFGL

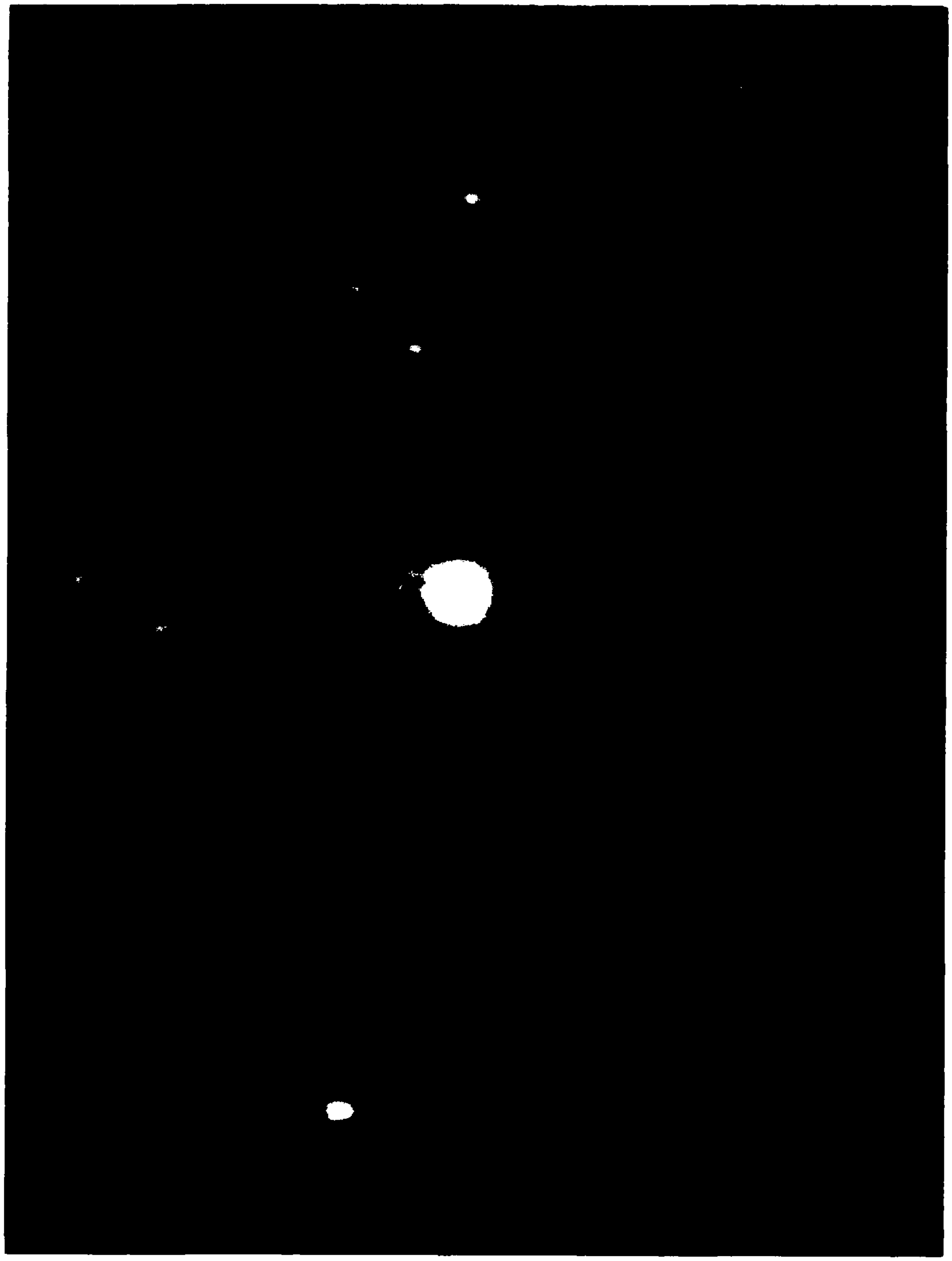

Figure 1. Video image of the 7774Å glow at 0520 UT, 9 Nov 1983 (40 sec after release). Note that many of the dot images are not stars (also in Fig's 2-3).

Figure 3. Video image of the 7774Å glow at 0522 UT, 9 Nov 1983 (160 sec after release).

While such large errors are usually indicative of one or more stars which have been misidentified, the problem here appears to be associated with a (presumably radially symmetric) off-axis distortion commonly found in very wide angle camera systems associated with its variation in focal length with angular distance from the optic axis. Compensation for this lens distortion was attempted several times with little or no improvement in the resulting optic axis direction vector error. The distortion curve used, shown in Fig 4, was taken from a 90° field, 0.345 cm focal length lens of broadly similar design and shifted to coincide with the measurable distortion at the locations of identifiable stars. Stars used to measure this distortion were digitized from a video frame taken through a 6300A° filter where many more stars are identifiable than in the the near-IR 7774° images. (There were still insufficient stars to adequately determine the distortion curve.) Note that the optical system used with the image intensifier camera has a relatively complex telecentric lens similar to Fig 5, with the complexity deriviving mainly from the small ray divergence needed at the position of the interference filter to obtain a nearly monochromatic response at all off-axis angles.

A further factor that affected the distortion correction was inability to accurately locate the center of the circular image (optic axis). That is, the correction as applied may have been asymmetric. (The optical system lacked fiducial markers for establishing a coordinate system in the film plane, and hence the optic axis). We located the center by reference to several points on the (relatively diffuse) edge of the circular field of view. Primarily the vertical and horizontal diameters were bisected to obtain the center point, since obvious irregularities exist over most of the circumference.

Mislocation of the optic axis not only affects the distortion correction, but also shifts coordinate locations (relative to the axis) and adversely affects coordinate transformations (rotations about coordinate axes) performed during orientation and triangulation calculations.

In order to establish the optic axis direction vector in a manner which, while not precise, would be consistent from frame to frame, it was decided to use only the two stars nearest to the center in each case. The best estimate of the image plane position of the optic axis was used and the assumption made that there was zero lens distortion. The star image digitization program which predicts the image plane location of stars in the field of view was then run for several focal lengths ($0.28 < f < 0.34$ cm). The focal length resulting in the best match ($f = 0.31$ cm) of predicted with actual measured positions for the two star images was chosen as the effective focal length for use in determining the direction vector.

Finally, the direction vector was determined for each frame using these same two stars. These are shown in Table I expressed in the horizon system. Although no standard deviations may be calculated from a two star determination some worst case (assuming ± 1 pixel error in star coordinates) estimates of error for these data are also shown. More realistic estimates based upon the interpolation used to locate the star image coordinates are on the last line of the table. (Interpolations were done to 1/10 pixel and a ± 1/5 pixel error assumed). The angular errors translate to spatial errors of $\sim$1.2 km at ranges of $\sim$350 km. Since the release image is located near the center of the frame, the large tilt (rotational) error produces only a very minor error in spatial location of the glow.

3. Triangulation and Velocity

Since images of the release were only available from one observation site, a single site triangulation (projection) was used to determine the spatial position of the glow as a function of time. This method assumes that the altitude of the glow is known, scales the line of sight vector to the glow to intersect the assumed altitude, and calculates the latitude and longitude of this point.

Briefly, the image plane glow coordinates were converted to a vector in the camera system. Then utilizing the camera azimuth, elevation, and tilt (calculated above from the star field), the camera location (latitude, longitude, altitude), and the exact time that the image was exposed, a series of coordinate transformations converted the camera vector to a geocentric coordinate system vector L. The vector ρ_C from earth center to the camera was then calculated from an ellipsoidal earth model. An iterative procedure then added ρ_C + $AL = \rho_G$ where A is a scale factor to change the length of L and ρ_G is the vector from earth center to the glow. As each ρ_G was obtained, the earth model was used to calculate the latitude, longitude, and altitude Z defined by ρ_G. If Z did not equal the assumed glow altitude H, A was modified and another iteration performed until $Z = H$. Latitudes and longitudes thus determined for a series of time separated images provide the basis for determining glow velocity. Altitude precision is estimated as approximately ± 2 km based upon camera orientation errors.

Table II shows spatial positions determined from the images based upon two assumptions concerning the vertical velocity V_v of the glow. Included in the data is the rocket trajectory position at the time of release. The first set of data assumes that $V_v = 0$, that is the altitude does not change with time. It has been observed however, that the altitude of the region of maximum radiating material density decreases with time. Computer assisted calculations (Ref 1) show the fall rate to average ~112 m/sec in the first 40 sec, ~46 m/sec in the next 60 sec, and ~38 m/sec in the following 60 sec. The altitudes used for the triangulation position determination for the second set of data in Table II were obtained from these calculations and are also shown in Fig 6. Horizontal velocities were calculated from the position differences and are shown for each time interval. Average velocity over the total interval has been determined from least squares analysis of positions. Position north and south relative to release point and the velocity for each time interval are shown in Fig's 7 and 8.

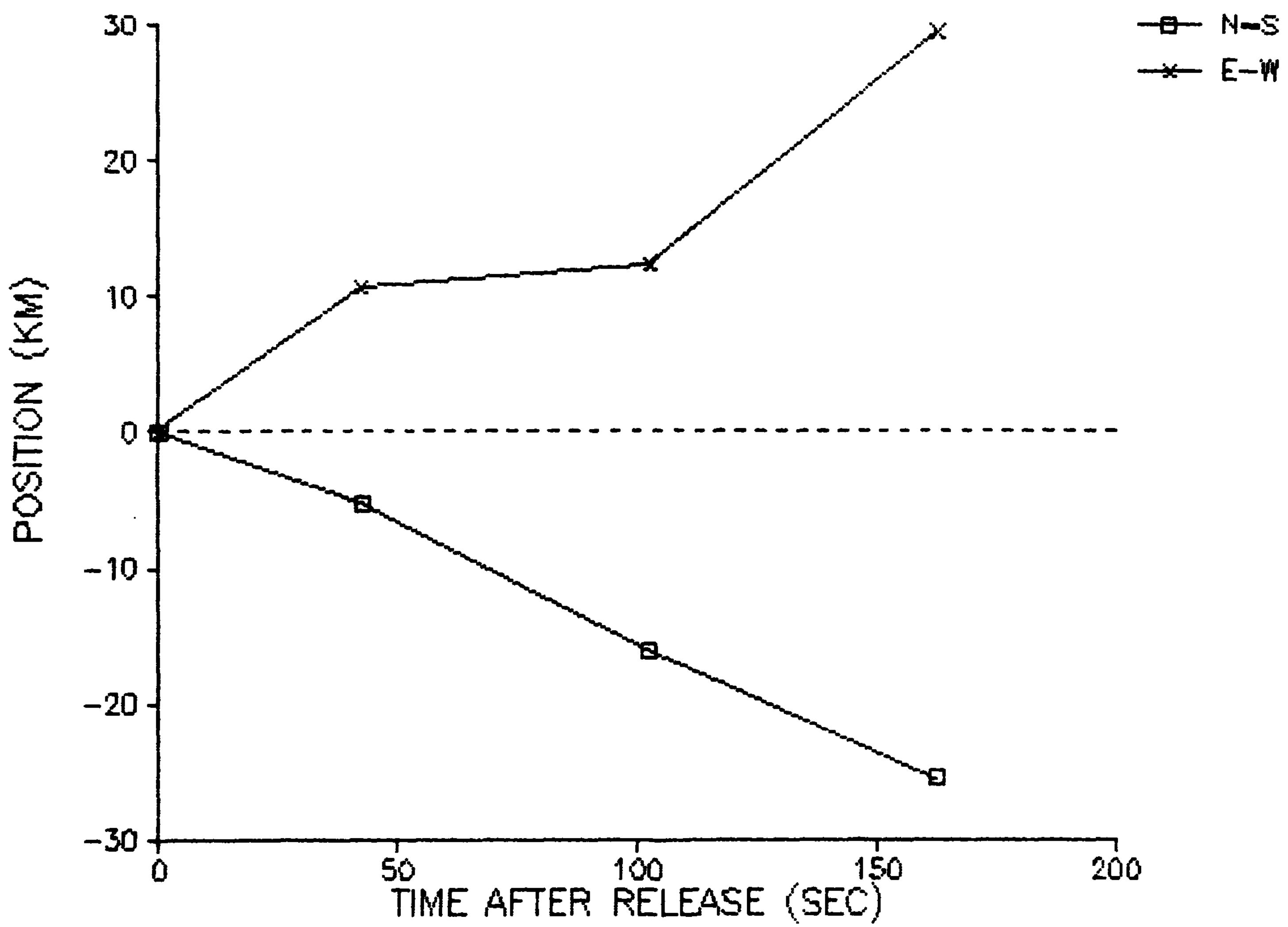

Figure 7. **Horizontal position of the glow relative to release point at times 0520, 0521, 0522 UT assuming that the glow region is decreasing in altitude.**

4. Growth of the SF_6 Induced Glow

The rate of growth of the image of a tracer glow may be used to determine the rate of diffusion of the tracer (or its reaction product(s)) into the ambient atmosphere (Ref 6). Only relative exposure (irradiance x time) need be recorded in the image (photographic or electronic) to determine the diffusion coefficient. Changes in the "gain" of the recording system (lens aperture or electronic amplification) may also effect the gaussian width, in that the slope of the curve of display intensity vs faceplate irradiance would change. The assumption was made that the response of the image intensifiers and vidicon to irradiances was linear over the small brightness range exhibited at 7774Å°.

The recorded image is a composite of exposure due to the glow and that due to background (night sky in this case). This background must be subtracted leaving only the glow exposure itself, which is typically gaussian, to be analyzed. The diffusion coefficient is

$$D = (h^2 - h_o^2)/4(t - t_o)$$

where h and h_o are the glow exposure halfwidths at time t and t_o. For a gaussian glow h^2 is best determined from a least squares fit of ℓn E and r^2 where E is the glow exposure at distance r from the glow center. The slope derived from this fit is $-1/h^2$.

The equation for D has been used extensively even when the glow is not strictly gaussian (the least squares analysis straight line will not necessarily be indicative of h^2), however h is measured directly from the glow image distribution at the point where exposure = $1/e^{th}$ of the peak glow exposure. For a gaussian distribution there is no difference between

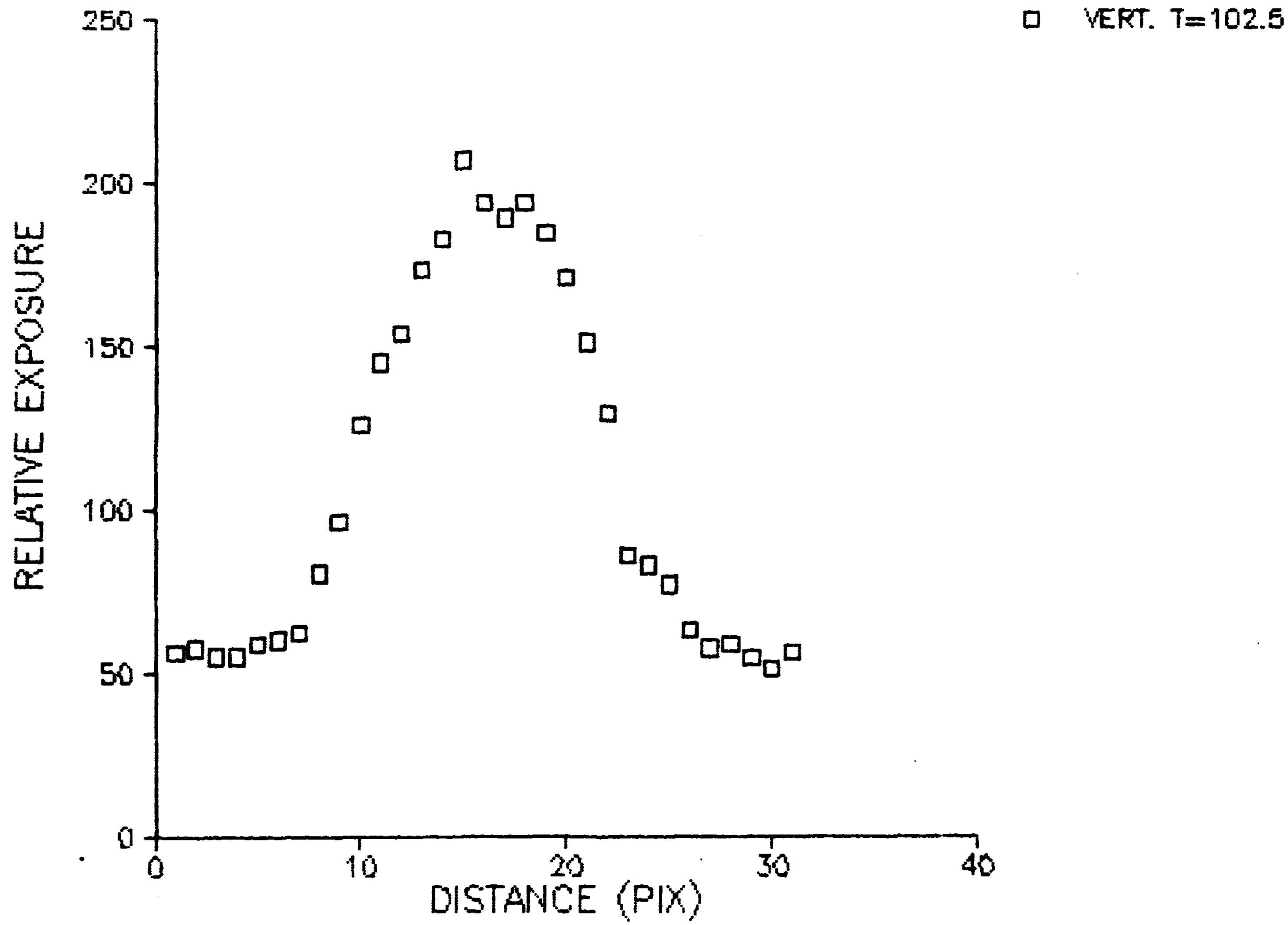

Figure 10. Relative glow exposures at 0521 UT along a vertical slice in the image plane.

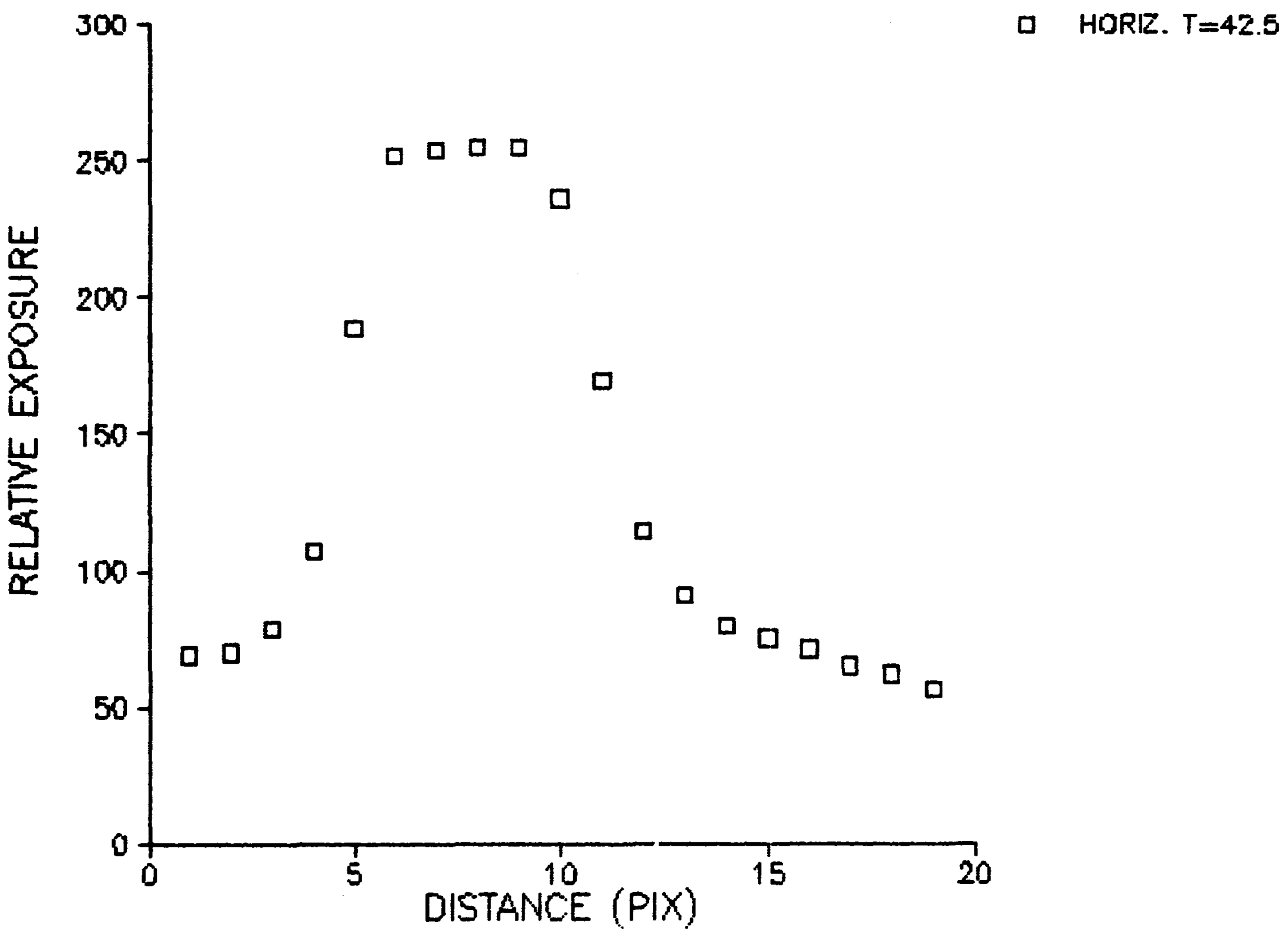

Figure 12. Relative glow exposures at 0520 UT along a horizontal slice in the image plane.

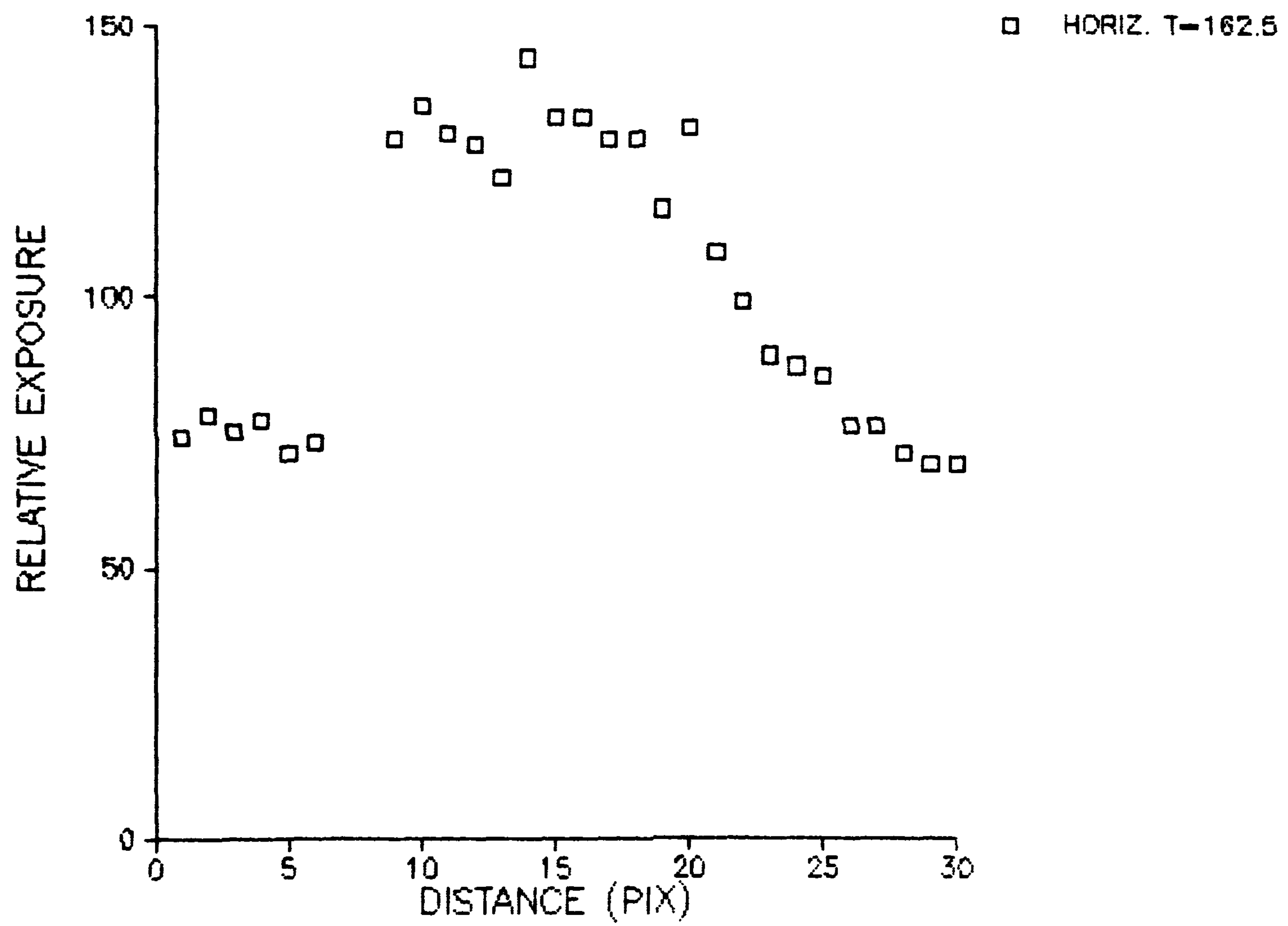

Figure 14. Relative glow exposures at 0522 UT along a horizontal slice in the image plane.

Table III. Measured and averaged values of SF_6 glow halfwidths. An average slant range of 336 km and focal length of 0.31 cm were used to obtain spatial halfwidths.

TIME (sec)	h IN IMAGE PLANE (cm)	h AT GLOW (cm)	h^2 AT GLOW (cm^2)	
42.5	.01835	1.98×10^6	3.95×10^{12}	
102.5	.02802	3.04×10^6	9.28×10^{12}	HORIZONTALLY IN IMAGE PLANE
162.5	.03695	4.00×10^6	1.60×10^{13}	
42.5	.01618	1.75×10^6	3.07×10^{12}	
102.5	.02474	2.68×10^6	7.19×10^{12}	VERTICALLY IN IMAGE PLANE
162.5	.02753	2.98×10^6	8.90×10^{12}	
42.5		1.86×10^6	3.47×10^{12}	
102.5		2.86×10^6	8.17×10^{12}	AVERAGE
162.5		3.49×10^6	1.21×10^{12}	

5. Conclusions and Recommendations

Image intensified video records of the 7774Å OI emission induced by a release of sulfur hexafluoride molecules into the atmosphere have been analyzed using the AFGL Coordinate Digitizer/Image Analyzer. Camera axis direction vectors were obtained by analyzing the recorded star fields and spatial position of the glow and its range from the camera determined by single site triangulation (projection). The atmospheric wind (velocity of the glow) was deduced from a time sequence of cloud positions. Further analysis was conducted to determine the growth rate of the released material into the ambient atmosphere, from which an effective diffusion coefficient was derived. No geomagnetic confinement of the glow species was detectable. With absolute radiometric calibration data, we would be able to assess the absolute surface brightnesses of the glow (from which column densities of reactants could be inferred.)

Use of this intensified and filtered imaging system has provided the first measurements of atmospheric wind and diffusion at thermospheric altitudes above ~250 km. In addition it provided information on the atmospheric chemical reactions of SF_6 and its successor species. Two such cameras, widely separated, would allow true triangulation to such glows and more precise wind measurements. A measurement of the lens focal length as a function of off-axis angle would improve the triangulation accuracy, and application of the absolute photometric response of the camera would result in still further useful information about both the ambient atmosphere and the reactions resulting from the chemical release.

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